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# Aging Characteristics of an Aluminum-4.5% Copper-1.5% Magnesium Alloy

Robert Earl Sulouff
*University of Central Florida*

# AGING CHARACTERISTICS OF AN
# ALUMINUM-4.5% COPPER-1.5% MAGNESIUM ALLOY


BY

ROBERT EARL SULOUFF JR.
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THESIS

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## ABSTRACT

The effects of quenching conditions, single-step and two-step aging treatments on the tensile properties of an Al-4.5%Cu-1.5%Mg alloy has been investigated. Results indicate that two distinctly different precipitates of GPB and S' form during aging. Single-step aging at 140°C, 160°C and 190°C indicated that 24 hours at 160°C produced optimum strength (67 ksi UTS). Two-step aging for 3 days at 140°C plus 190°C resulted in a slight increase in strength over single-step aging at 190°C. Slow (oil) quenching as well as direct quenching improved the tensile properties when aged at 190°C. Reversion occurred slowly over the temperature range 250°C to 350°C.

# ACKNOWLEDGMENT

I wish to express my personal thanks to the many people concerned with the completion of my Master's Thesis and Degree.

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# INTRODUCTION

The age hardening of aluminum-copper-magnesium alloys has been studied extensively. The formation of a new phase upon cooling which is dependent upon the diffusion aspects in the solid state is the basis for the phenomena. The improvement in mechanical properties is due to a resistance to plastic deformation due to the clustering (precipitation) of the insoluble material at a critical dispersion [1]. The evaluation of X-ray data which lead to the discovery of G.P. zones has explained the precipitation of the copper in aluminum upon aging [2].

The development in the understanding of the nature of the precipitation mechanism did not meet with major milestones until after the early 1950's. An extensive review of the information on aluminum-copper-magnesium in 1954 by Hardy [3] indicated an understanding of the effects of specific heat treatments without a clear explanation of the cause. The quicker response of alloys with the addition of magnesium and some general conclusions with regard to reversion provided the major results prior to the early 1950's.

## Precipitates in Aluminum-Copper-Magnesium

The aluminum-4.5%copper-1.5% magnesium alloy is a pseudo-binary material forming an alpha and S phase ($Al_2CuMg$) at temperatures below 507$^\circ$C [4]. The metastable S' phase is nucleated prior to the formation of the incoherent precipitates of the lath shaped S phase [5]. The major strengthening effects in this alloy occur as the homogenously nucleated GPB zones are precipitated in correct distribution and size along with the early precipitation of the S' phase [6]. Information relating to each specific precipitate will be discussed in this section .

GPB zones

The formation of the GPB zones is due to the supersaturation[17] encountered upon cooling from the solutionization temperature. The four percent smaller atoms of copper by volume with respect to aluminum are offset by the fourteen percent larger atoms of magnesium. As the material is cooled from its solutionization temperature the nucleation and growth of aggregates of copper and magnesium on (100) planes of aluminum occur [6]. Earlier work by Hardy [3] who used x-ray diffraction techniques labeled these zones as G.P.(1,Cu) and G.P. (1,S). The possibility of a series of solutions of G.P.(1,Cu, Mg) forming from G.P.(1,Cu) and G.P.(1,S) was also presented by Hardy [3]. Silcox [6] examined the alloy system and identified the G.P. zones as G.P.B. due to the fact that the correlation between the S phase and the zones is questionable. The smaller size of the GPB zones (approximately 10Å to 30Å) and the lack of strains introduced in the matrix at the early stages make examination with the electron microscope unprofitable [7]. The role of vacancies in the formation of GPB zones provides an explanation of the high diffusion observed with this alloy [8]. The binding energy associated with the vacancies and solute atoms in this alloy is believed to contribute to a metastable vacancy enriched GPB zone [9]. The formation and stability of GPB zones has been evaluated by reversion experiments [10]. The formation of specific zones and the subsequent resolution of the zones due to a higher temperature has been an effective means of identifing the upper limits of stability. Sen and West [11] have evaluated the stability of the GPB zones and found the upper limit to be 260°C.

The formation of GPB (2) structure has been noted by Silcox [6]. The analysis of the structure with x-ray diffraction indicated a third dimension appearing in the GPB structure. Some of the spots were in the position of the S' precipitate spots, but some were also in new positions. This development was noted only after aging above 240°C. Silcox [6] has also made comment as to the high hardness values associated with the GPB (2) structure.

S' and S zones

The supersaturation of the binary aluminum plus $Al_2CuMg$ phase results in a transformation to the S phase ($Al_2CuMg$) which is incoherent with the matrix when sufficient energy is available to cause the phase to grow [12]. The S' phase preceeds the S phase. The S' phase has been one of the more completely investigated precipitates in this alloy system [5]. The peak hardness has been found to occur during the formation of the S' precipitates [6]. The orientation relationship of the S' precipitate to the aluminum matrix is:

$$[100]_S//[100]_{Al};[010]_S//[021]_{Al};[001]_S//[012]_{Al}$$

as reported by Silcox [6]. The S' precipitate is orthorhombic with a= 4.00, b= 9.23, and c= 7.14 Å [6]. The misfit of this precipitate is accommodated by dislocations which act as nucleation sites [13].

Nucleation and Clustering of Precipitates

The nucleation process occurs during the quenching of the alloy [6]. The quench rate is known to influence the aging response of aluminum-copper-magnesium alloys [6,8,11]. The precipitation sequence occurs with two different precipitates. The GPB zones nucleate homogenously during the quench and initial aging. The presence of vacancies in the supersaturated solid solution enhance the diffusion of atoms and allow for rapid nucleation of the GPB zones [14]. The formation of the S' precipitate occurs as lath shaped particles which commonly nucleate on dislocations [15]. The S' laths nucleate as a function of three energy changes, the volume free energy change, the strain energy change and the increase in interfacial energy due to the new precipitate-matrix boundary [5].

High temperatures and extended times are required to produce stable S' precipitates that contribute to the mechanical strength of the alloy [6]. The formation of the S' precipitate is not dependant upon the GPB zones [13]. The electron microscope investigation of S' precipitation by Wilson and Partridge [5] developed both the nucleation and growth kinetics of the S' precipitate. The influence of the interfacial energy upon the growth of S' precipitates is significant. The recent theoretical presentation by Russel and Aaronson [20] indicate the dominance of this factor. The formation of dislocation loops due to the quenched in vacancies is an important factor in the nucleation kinetics of the S' precipitate.

Strengthening Methods and Properties

The mechanical properties of age hardened aluminum alloys has been the primary evaluation mechanism since its early discovery. The hardness of aluminum-copper-magnesium increases with the precipitation of the GPB and S' zones [3]. The correlation between hardness and x-ray diffraction has been demonstrated as an effective tool to correlate the structure and mechanical properties [6]. The initial precipitation of GPB zones results in an increase in strength of the alloy [16]. The formation of the metastable S' phase contributes to the strengthening effects also. The study by Robinson and Hunter [16] found values of 63ksi ultimate tensile strength(UTS) and 20 percent elongation for GPB zones formed from water quenching and room temperature aging in Al-4.5%Cu-1.5%Mg. The published data indicates [22] that typical values for age hardened Al-Cu-Mg at 190°C is 70ksi UTS and 8 to 12 percent elongation. This data does not refer to the same composition (0.5%Mn added) or actual heat treatment conditions of the research alloy evaluated. The additional 0.5% Mn and different quenching conditions can play an influencial role. This data is presented as the typical application oriented information for comparison purposes.

# RESEARCH OBJECTIVE

The purpose of this research was to examine the effects of different quenching conditions and heat treatments on the tensile properties of an aluminum-4.5% copper-1.5% magnesium alloy. The different quenching conditions were water quench and oil quench to 20°C and direct oil quench to 190°C. The heat treatments were single-step and two-step aging treatments and reversion. The tensile properties investigated were the ultimate tensile strength, yield strength and the elongation of the samples.

## EXPERIMENTAL PROCEDURE

The composition (see Table 1) of the sample was evaluated following the prescribed heat treatments. The alloy was direct chill cast into a 3 by 8 by 12 inch ingot which was homogenized at 500°C, scalped and hot rolled to 0.125 inch thickness sheets and then cold rolled to 0.025 inches using several intermediate annealing treatments. The 0.025 inch sheets were then sheared into 2.0 by 0.25 by 0.025 inch blanks and machined into tensile test specimens with a reduced section of 0.5 by 0.125 inches. Prior to all aging treatments, all of the samples were given solid solution heat treatments at 500°C for 20 minutes in a furnance which was controlled to ± 3°C. After the solution heat treatment, the samples were quenched into the prescribed media (this being the quenching referred to throughout the text) and aged in a bath of Ucon Heat Transfer Fluid controlled to ± 1°C.

TABLE 1

CHEMICAL ANALYSIS OF MATERIAL *

| Cu | Mg | Si | Fe | Mn | Cr |
|---|---|---|---|---|---|
| 4.40 | 1.49 | 0.01 | 0.01 | 0.01 | 0.01 |

| Ni | Zn | Ti | Ag |
|---|---|---|---|
| 0.01 | 0.01 | 0.01 | 0.01 |

* All percentages in wt. %

Single-step and two step aging and reversion treatments were performed on the alloy to determine the characteristics under different aging conditions. Single-step aging treatments were performed at 140°C, 160°C and 190°C for various times. The effect of quench rate upon aging at 190°C was performed. The effect of two-step aging was performed by aging at 80°C for 1 week followed by aging at 190°C, aging at 140°C for 3 days followed by aging at 190°C and aging at 80°C for 1 week followed by aging at 160°C. The effect of direct quenching to the aging temperature (190°C) was performed. Reversion experiments were accomplished by aging at 190°C for 10 hours following a water quench, then 15 minutes at temperatures between 250°C and 350°C. A summary of the aging treatments is given in table 2.

After the heat treatments, the samples were tested for ultimate tensile strength, 0.2% offset yield strength and elongation using a 10,000 lb Instron machine. (0.1 inches per minute) and an Instron strain gage extensometer. All samples were tested at room temperature in duplicate. In cases where obvious discrepencies in the results occurred additional tests were made.

TABLE 2

SPECIMEN AGING TREATMENTS

Aluminum-4.5% Copper-1.5% Magnesium

All samples were initially solution heat treated for 20 minutes at 500°C and quenched into the prescribed media.

Single-Step Aging

(water quenched)

a. aged at 140°C (up to 1 week)
b. aged at 160°C (up to 1 week)
c. aged at 190°C (up to 96 hours)

Two-Step Aging

(water quenched)

a. aged at 80°C for 1 week; aged at 160°C (to 96 hours)
b. aged at 80°C for 1 week; aged at 190°C (to 96 hours)
c. aged at 140°C for 3 days; aged at 190°C (to 96 hours)

Quench Rate Study

a. water quenched (20°C), aged at 190°C (to 96 hours)
b. oil quenched (20°C), aged at 190°C (to 96 hours)

Direct Quenching Study

a. water quenched (20°C), aged at 190°C (to 96 hours)
b. direct quenched to 190°C and aged at 190°C (to 96 hours)

Reversion

water quenched (20°C) and aged 10 hours at 190°C
15 minutes at either 250,275,300,325 or 350°C

# RESULTS

## SINGLE-STEP AGING

The effects of single-step aging at 140°C, 160°C and 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy are shown in Fig. 1 to 3. All samples for these aging treatments were solutionized at 500°C for 20 minutes and were water quenched at 20°C.

### (a) Aging at 140°C

The ultimate tensile strength (UTS) of the alloy increased rapidly from the as quenched value of 39.8 to 63.5 ksi within two minutes when aged at 140°C (Fig. 1). Further aging at 140°C up to 3 days produced no significant increases in UTS. After 7 days aging at 140°C the UTS rose to 64.3 ksi which is 2 ksi above the average UTS for two days aging at this temperature.

The yield strength followed the same trend as the UTS during aging at 140°C. That is, within the first 2 minutes the yield strength rose from 17.3 to 41.9 ksi. No further increase in yield strength occurred until after 3 days aging. Between 3 and 7 days at 140°C the yield strength increased to 45.3 ksi.

Ductility as measured by the percent elongation did not change significantly during the 7 days aging at 140°C and remained at 22±3%. Thus the alloy remained quite ductile during the whole aging period.

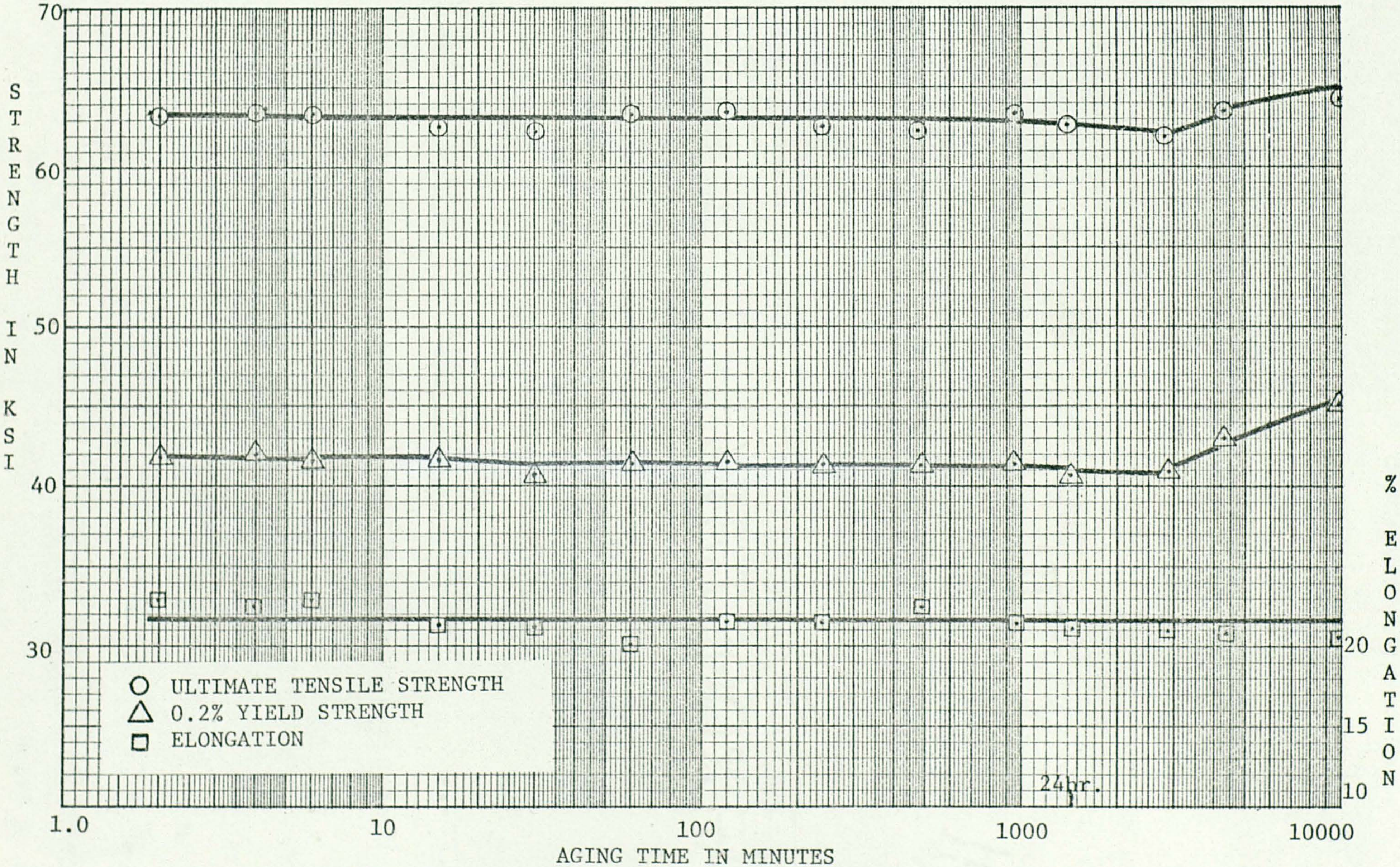


Fig. 1.--The effect of single-step aging treatments at 140°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

(b) Aging at 160°C

The ultimate tensile strength of the alloy increased rapidly from the as quenched value of 39.8 to 64.0 ksi in 2 minutes when aged at 160°C (Fig. 2). Further aging at 160°C up to 2 days produced no significant increase in UTS. In the interval between 2 and 7 days a peak of 67.5 ksi occurred at 3 days. The 7 day aging data indicated a decline to 63.4 ksi.

The yield strength followed the same trend as the UTS during aging at 160°C for the first 16 hours. That is, within the first 2 minutes the yield strength rose from 17.3 to 41.6 ksi. No further increase in yield strength occurred until after 16 hours aging. The yield strength then rose rapidly to 52.9 ksi in the 16 hour to 96 hour period. In the period between 96 and 144 hours the yield strength declined to a value of 51.4 ksi.

Ductility as measured by the percent elongation did not change significantly until after 16 hours aging where it decreased from the earlier value of 22±3% to a value of 9% after 144 hours aging. Thus the ductility of the alloy decreased significantly as the yield and UTS increased.

(c) Aging at 190°C

The ultimate tensile strength of the alloy increased rapidly from the as quenched value of 39.8 to 60.8 ksi in one minute and remained at this value for 2 hours (Fig. 3). Between the 2 and 4 hour interval the UTS increased to 65.2 ksi which was the maximum value attained at this temperature. Further aging beyond 4 hours decreased the UTS steadily and after 96 hours it had fallen to 52.7 ksi.

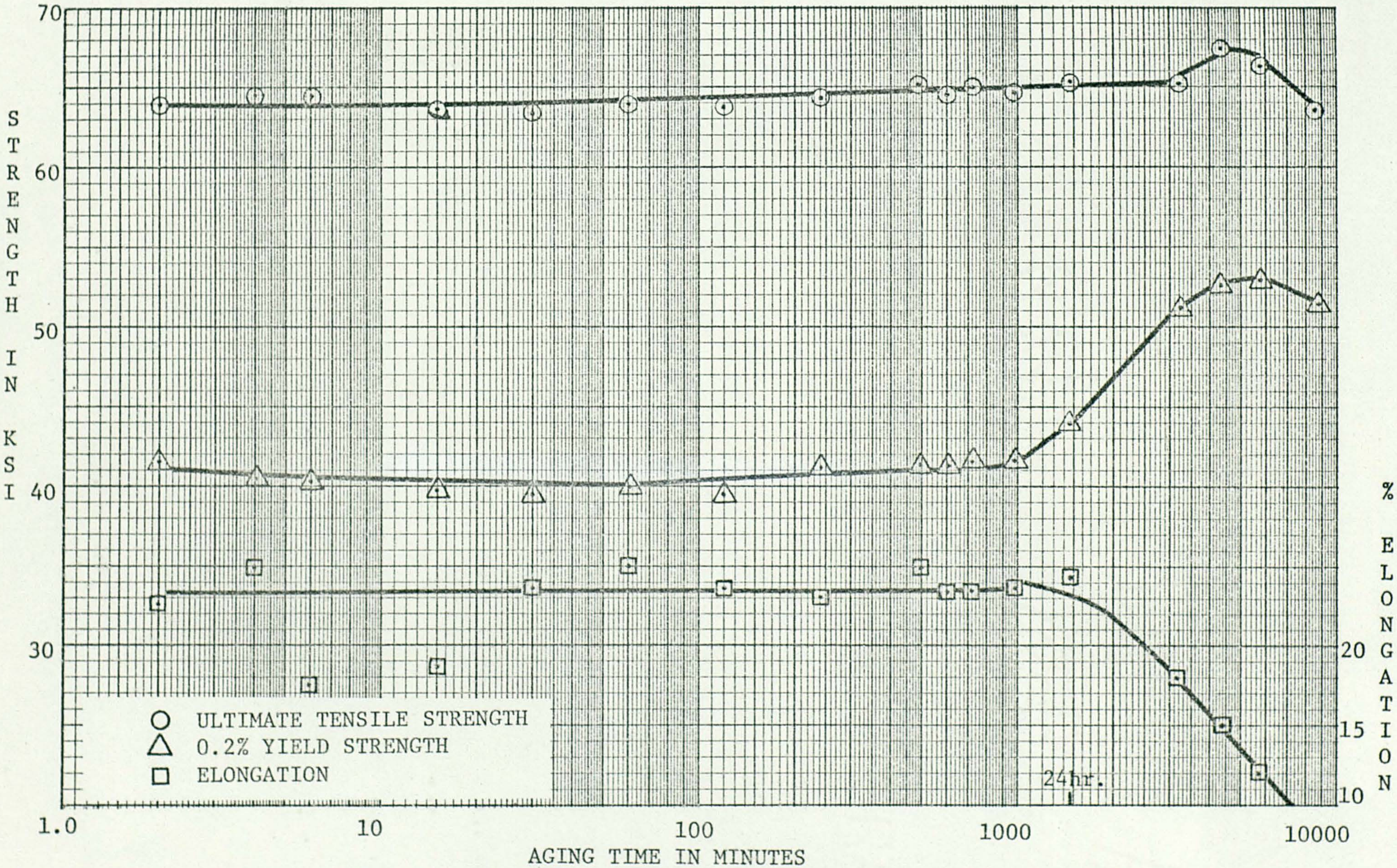


Fig. 2.--The effects of single-step aging treatments at 160°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

The yield strength followed the same trend in aging characteristics as the ultimate tensile strength except that the maximum yield strength was reached after 8 hours instead of 4. The yield strength approached the UTS value of 53 ksi as the maximum UTS was reached.

The elongation correspondingly decreased from 20±2% to 10±2% as the maximum UTS was reached. Further aging beyond the maximum decreased the elongation still further so that after 96 hours of aging the alloy had decreased to 5%.

A comparison of the ultimate tensile strengths for the aging temperatures of 140, 160 and 190°C is presented in Fig. 4. The influence of the temperature on the time to peak strength is noted. Aging at 190°C resulted in a peak UTS in 4 hours while aging at 160°C resulted in a peak after 72 hours. The 140°C aging indicated a trend to increased UTS after the maximum test time of 168 hours.

A comparison of the 0.2% yield strengths for the aging temperatures of 140, 160 and 190°C is presented in Fig. 5. The influence of the temperature on the time to peak yield strengths is also noted in this comparison. The peak yield strengths occur in the same time period as the UTS maximum.

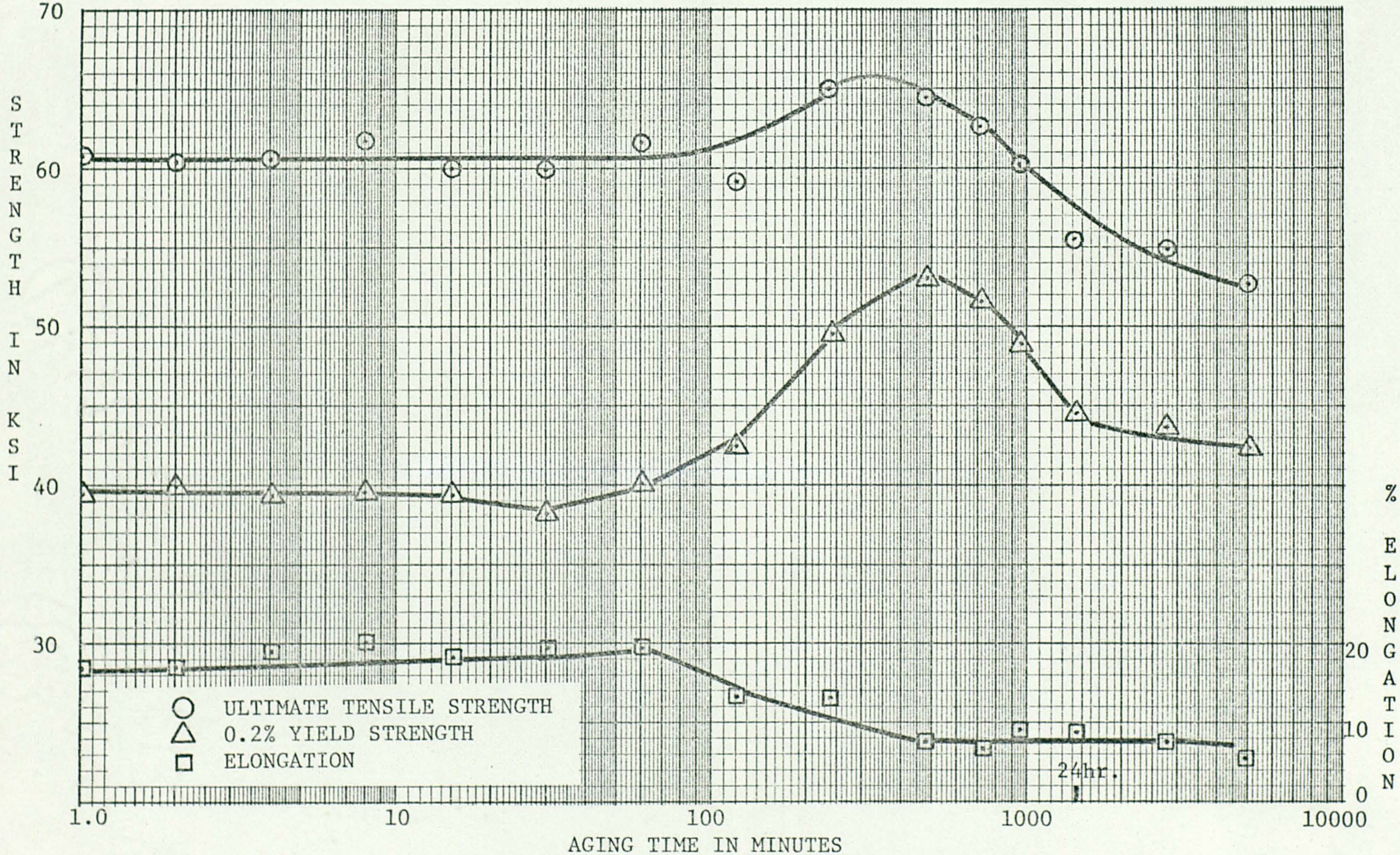


Fig. 3.--The effects of single-step aging treatments at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg

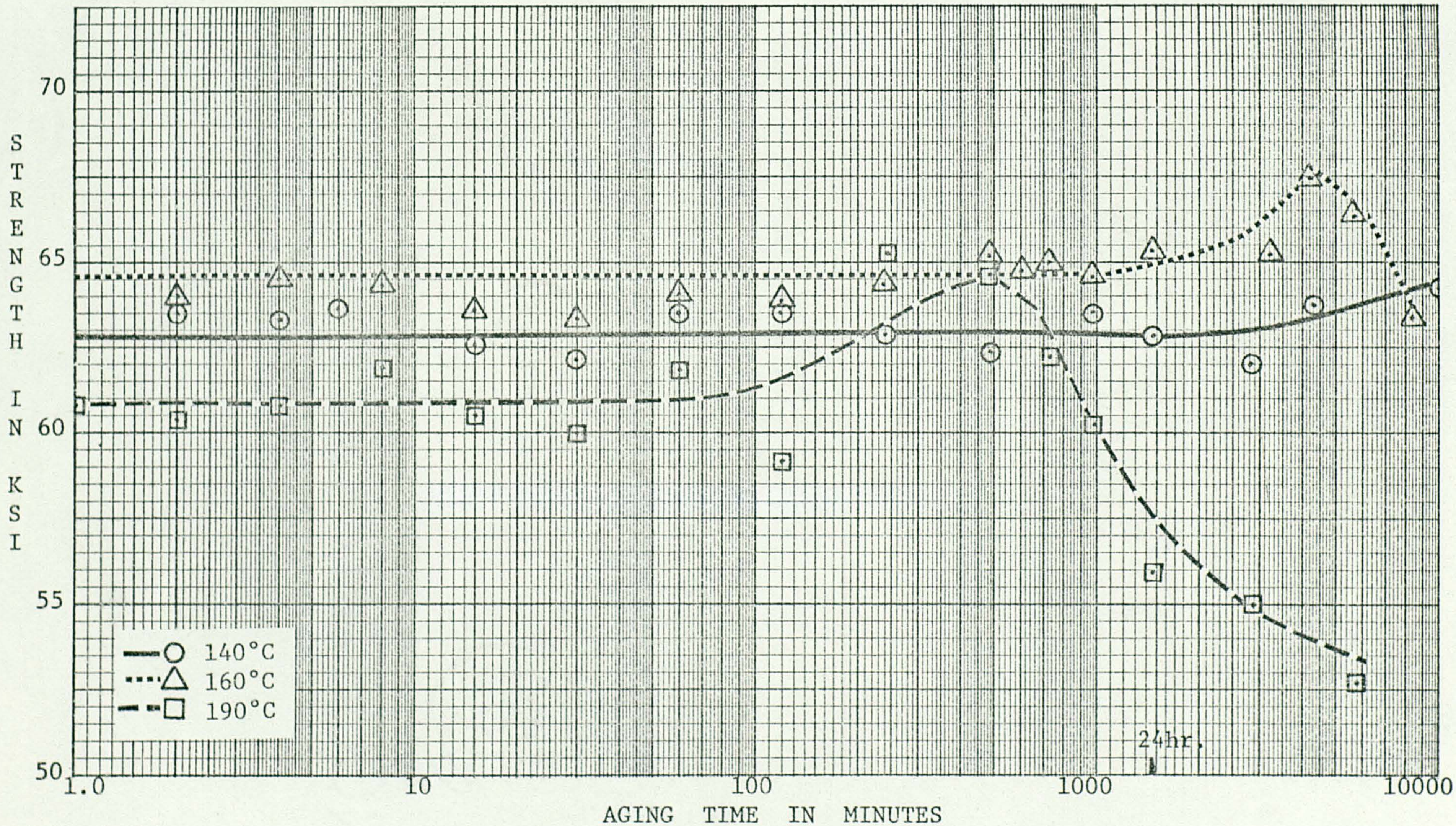


Fig. 4.-- The effects of single-step aging treatments at 140°C,160°C and 190°C on the ultimate strength of the Al-4.5%Cu-1.5%Mg alloy.

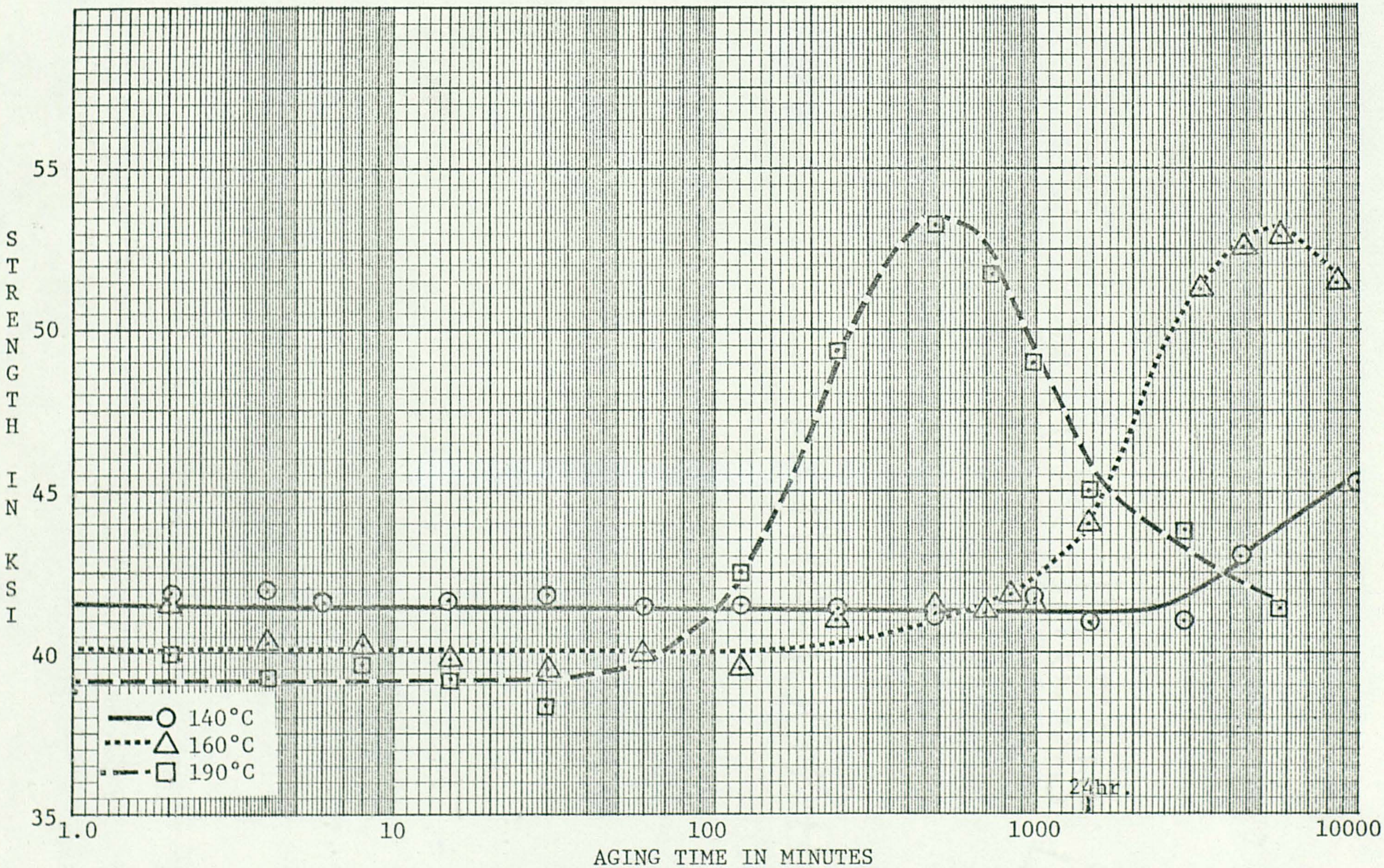


Fig. 5.-- The effects of single-step aging treatments at 140°C, 160°C and 190°C on the 0.2% yield strength of the Al-4.5%Cu-1.5%Mg alloy.

TWO-STEP AGING

The effects of two-step aging at 80°C (168 hr.) and 160°C, 80°C for 168 hr. and 190°C and 140°C for 72 hr. and 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy are shown in Fig. 6 to 11. All samples were solutionized at 500°C for 20 minutes and were quenched in water at 20°C.

(a) Aging 7 Days at 80°C Plus 160°C

As indicated in Fig. 6, the UTS after the 7 days (168 hr) at 80°C was 64.5 ksi. With one hour subsequent aging at 160°C the UTS decreased to 60.6 ksi. Further aging at 160°C led to a gradual increase in UTS to 64.5 ksi after 96 hours.

The yield strength followed the same trend as the UTS during aging at 160°C. A reduction from 42.5 ksi after preaging to 39.1 ksi after one hour at 160°C is noted. The yield strength then gradually increased from 39.1 ksi after one hour at 160°C to 43 ksi after 24 hours aging. Between 24 and 96 hours at 160°C the yield strength rapidly increased from 39.1 to 55.5 ksi.

Ductility as measured by the percent elongation did not change significantly until after 24 hour aging at 160°C and remained at 22±2%. In the period between 24 and 96 hours aging at 160°C the elongation decreased rapidly from 22 to 10% while the yield strength correspondly increased.

A comparison of the tensile properties of the alloy single-step aged at 160°C and two-step aged for one week at 80°C and then at 160°C is shown in Fig. 7. The UTS values for two-step aging are slightly lower throughout the whole aging process. The peak UTS

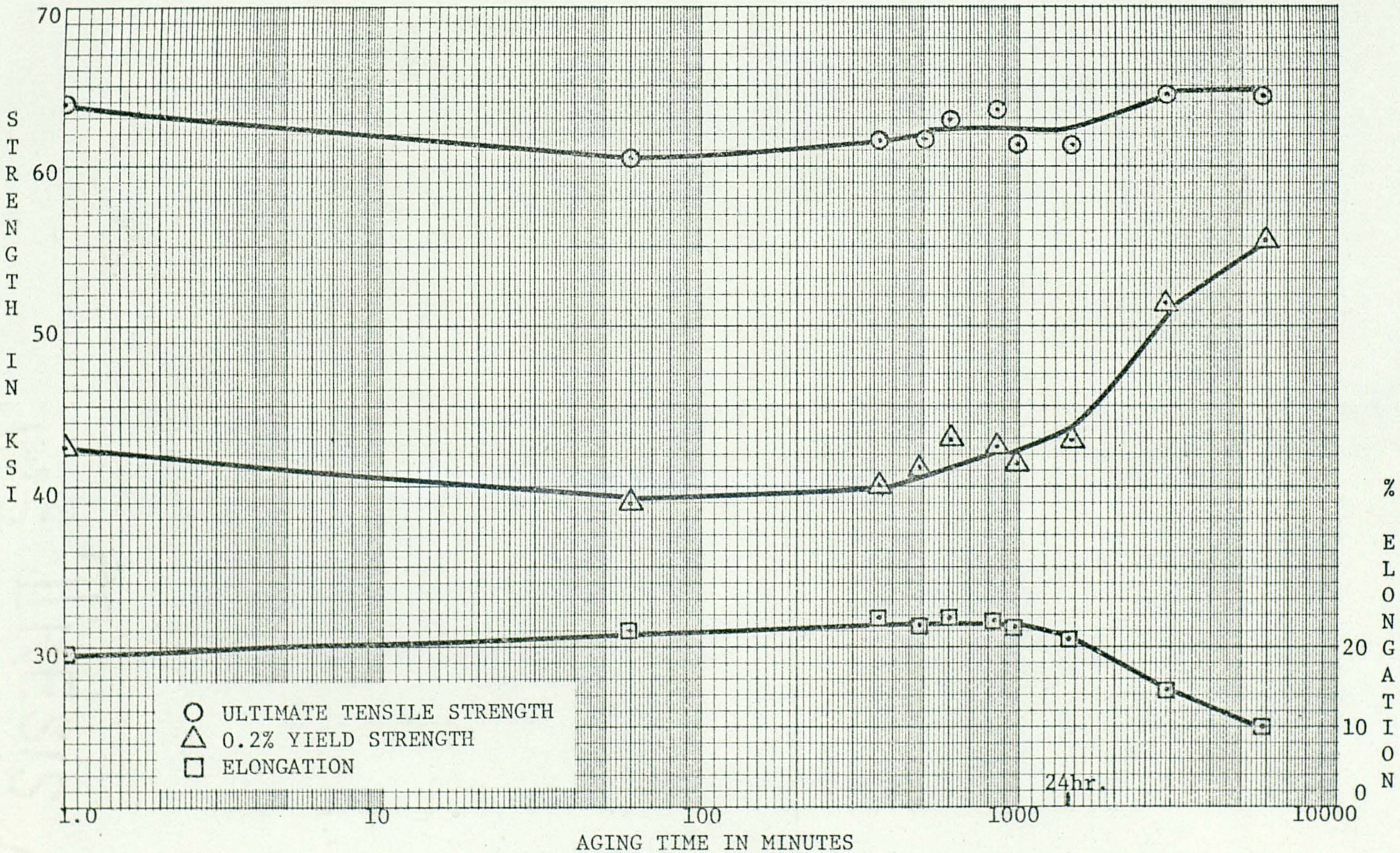


Fig. 6.-- The effects of two-step aging treatments at 80°C for one week plus aging at 160°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

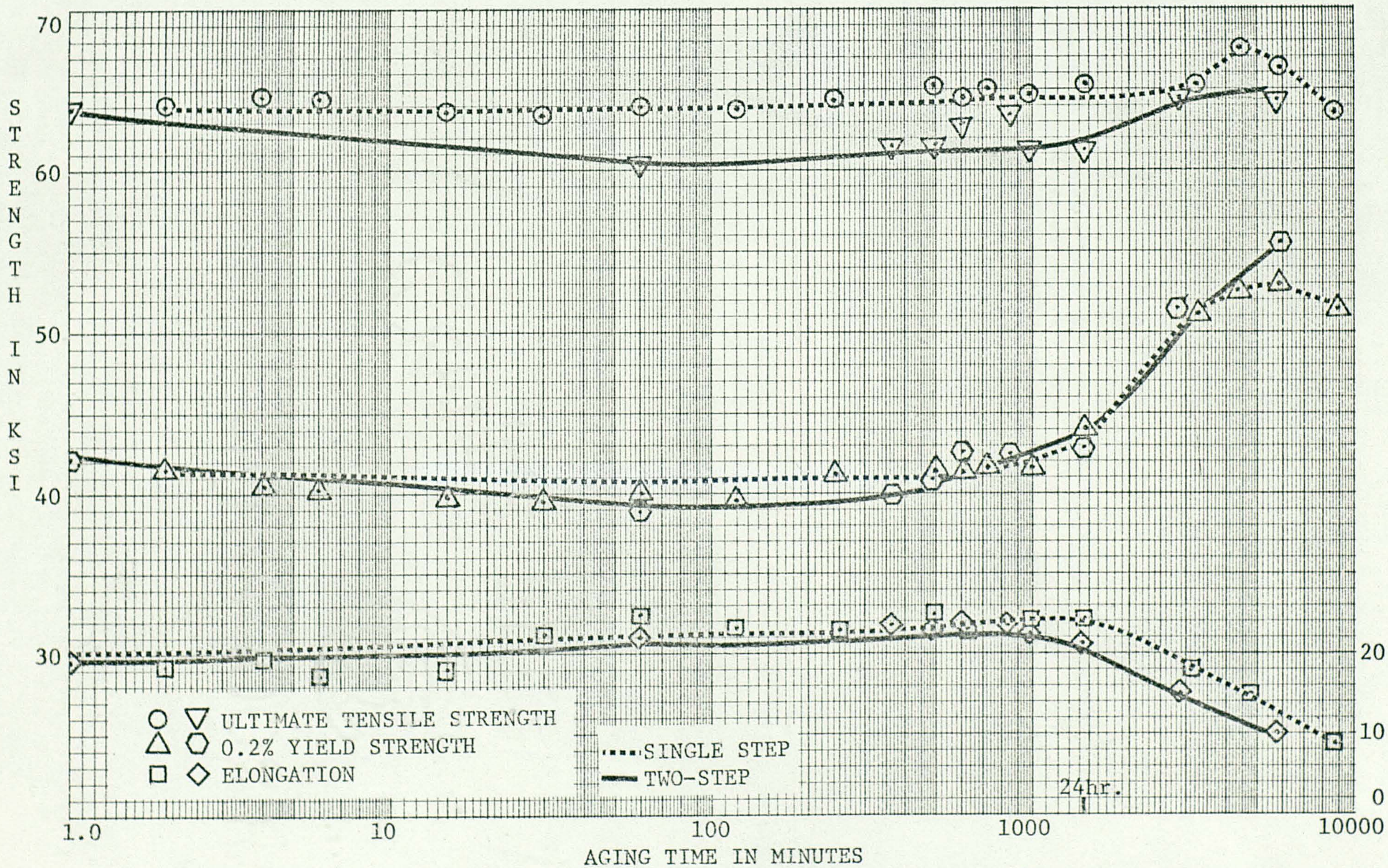


Fig. 7.-- A comparison of single-step aging at 160°C and preaging at 80°C for one week plus aging at 160°C on the tensile properties of the Al-4.5%Cu-1.5%Mg

value of the preaged and single-aged treatments occurred at about the same time of 72 hours aging. The UTS of the two-step aged alloy was slightly lower by 3 ksi at the peak occurring at 72 hours. After 96 hours aging at 160°C, the yield strength of the single-step aged alloy was slightly higher and its ductility slightly lower than the two-step aged alloy.

(b) Aging 7 Days at 80°C Plus 190°C

As is shown in Fig. 8. the UTS of the alloy preaged for one week at 80°C was initially decreased upon aging at 190°C. A minimum value of 58.1 ksi was reached after 2 hours aging at 190°C. Upon further aging at 190°C, the UTS increased reaching a maximum of 61.8 ksi after 6 hours aging. Aging beyond 6 hours led to a rapid decrease in UTS to 56.9 ksi after 16 hours and to a gradual decrease to 55.8 ksi after 96 hours.

The yield strength again followed the same trend as the UTS with a slight decrease in strength to 38.7 ksi occuring in one hour. This was followed by a rapid increase to 53.4 ksi after 6 hours. Further aging from 6 to 9 hours led to a slight decrease to 44.5 ksi after 96 hours. The ductility decreased from 25% after preaging one week at 80°C to 8.6% after 6 hours aging at 190°C. The minimum ductility corresponded to the maximum value of UTS and yield strength. Subsequent aging at 190°C led to a leveling of the ductility values to 9 to 10% in the period from 6 to 96 hours.

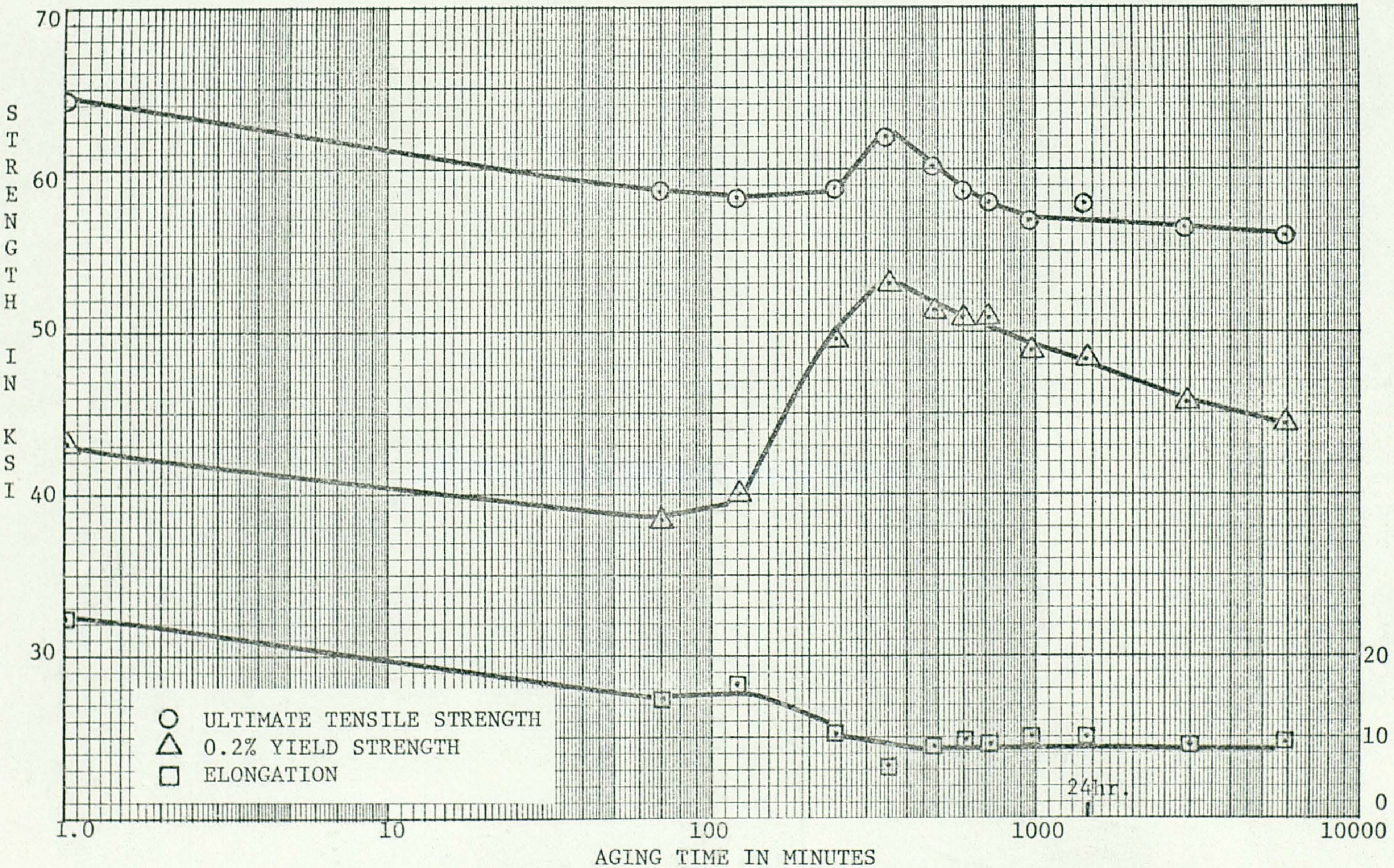


Fig. 8.--The effects of two-step aging treatments at 80°C for one week plus aging at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

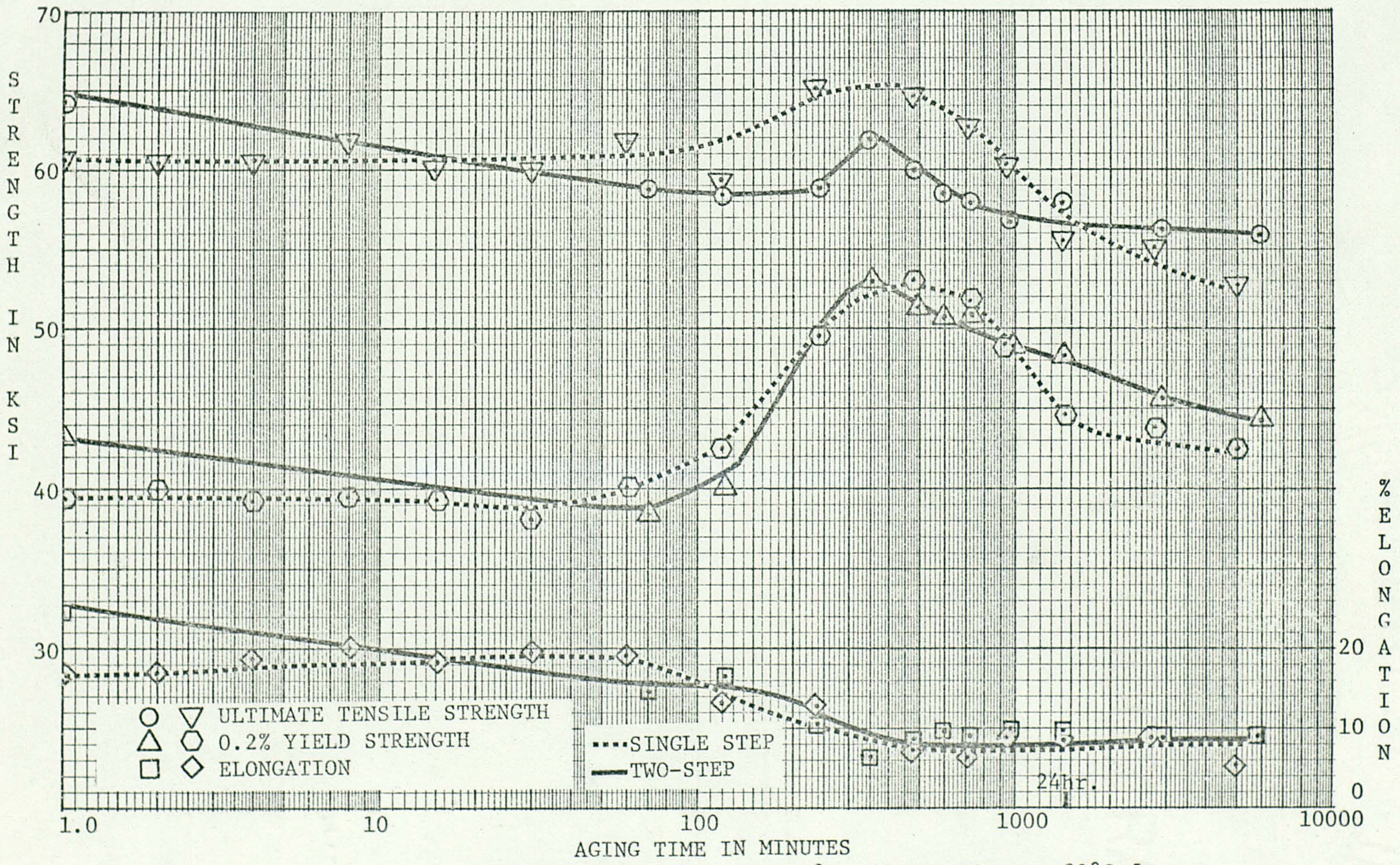


Fig. 9.--A comparison of single-step aging at 190°C and preaging at 80°C for one week plus aging at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy

A comparison of the tensile properties of the alloy aged at 190°C and two-step aged for one week at 80°C plus 190°C is shown in Fig. 9. The UTS for the two-step aged alloy was initially greater than the single-step aged alloy. Upon aging at 190°C the UTS of the preaged alloy after 2 hours had decreased to 58.1 ksi which is about 3 ksi lower than that of the single-step aged alloy. After 6 hours at 190°C the UTS of the preaged alloy increased to a maximum value of 61.8 ksi which is 3 ksi less than the peak UTS of the single-step aged alloy. The two-step aged alloy maintains its strength to a greater degree while the single-step alloy decreased in strength (overaged) more than the two-step alloy. The yield strengths of the two-step aged alloy followed the same trend as the UTS. The two-step aged alloy reduced in yield strength at a slower rate but arrived at the same value at the 96 hour point. The ductility values of the single-step aged alloy did not vary significantly from the two-step aged alloy.

(c) Aging 3 Days (72 hr) At 140°C Plus 190°C

Figure 10 shows the tensile properties of the two-step aging treatments of 3 days at 140°C plus aging at 190°C. The UTS decreased from the as preaged value of 64.1 ksi to 62.6 ksi after aging 2 hours at 190°C. Upon further aging the UTS rapidly increased to a value of 67.0 ksi after 4 hours. Further aging beyond 4 hours led to a rapid decrease to 59.5 ksi after 6 hours and subsequently to a gradual decrease to 56.5 ksi after 96 hours.

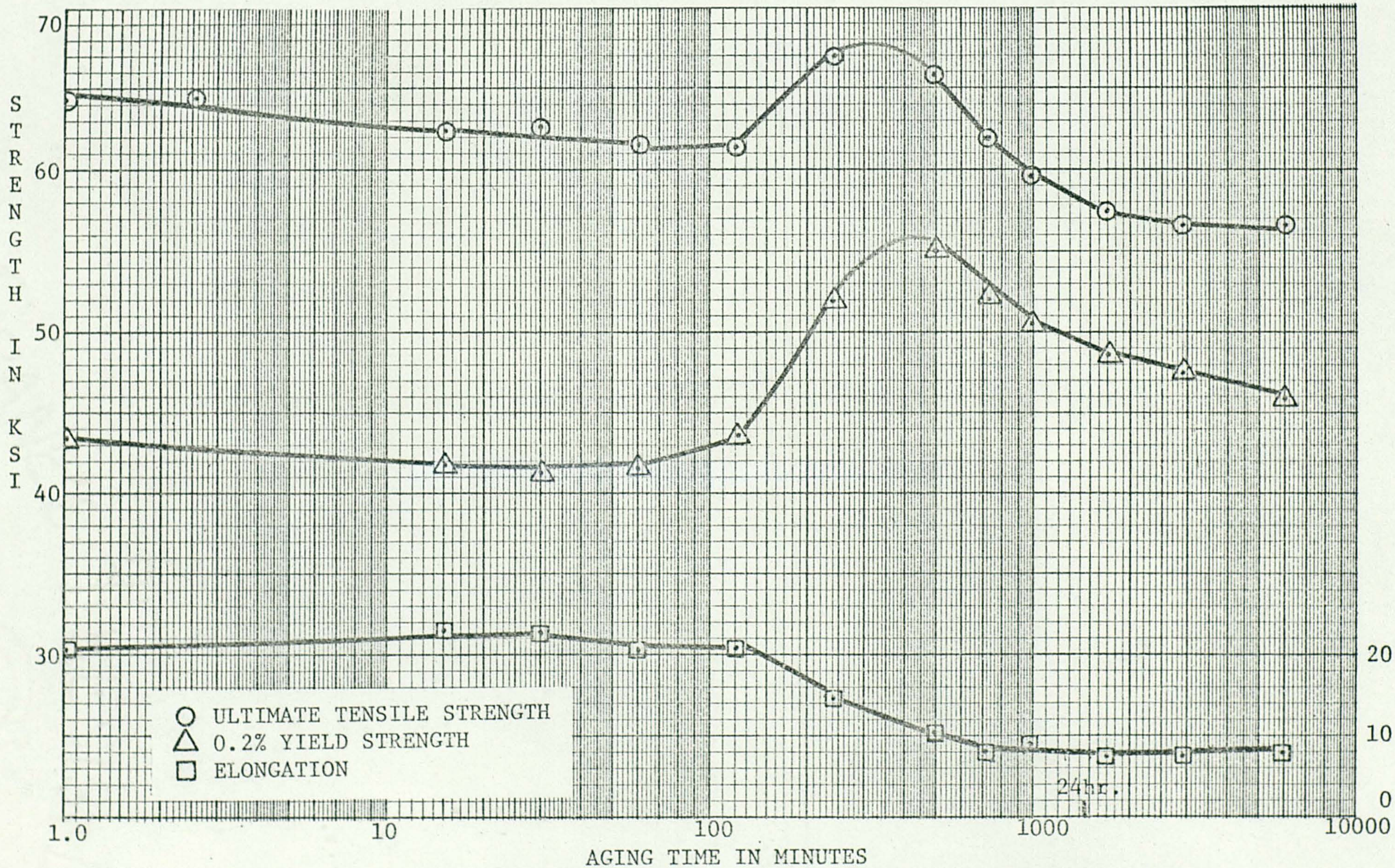


Fig. 10.--The effects of two-step aging treatments at 140°C for three days plus aging at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

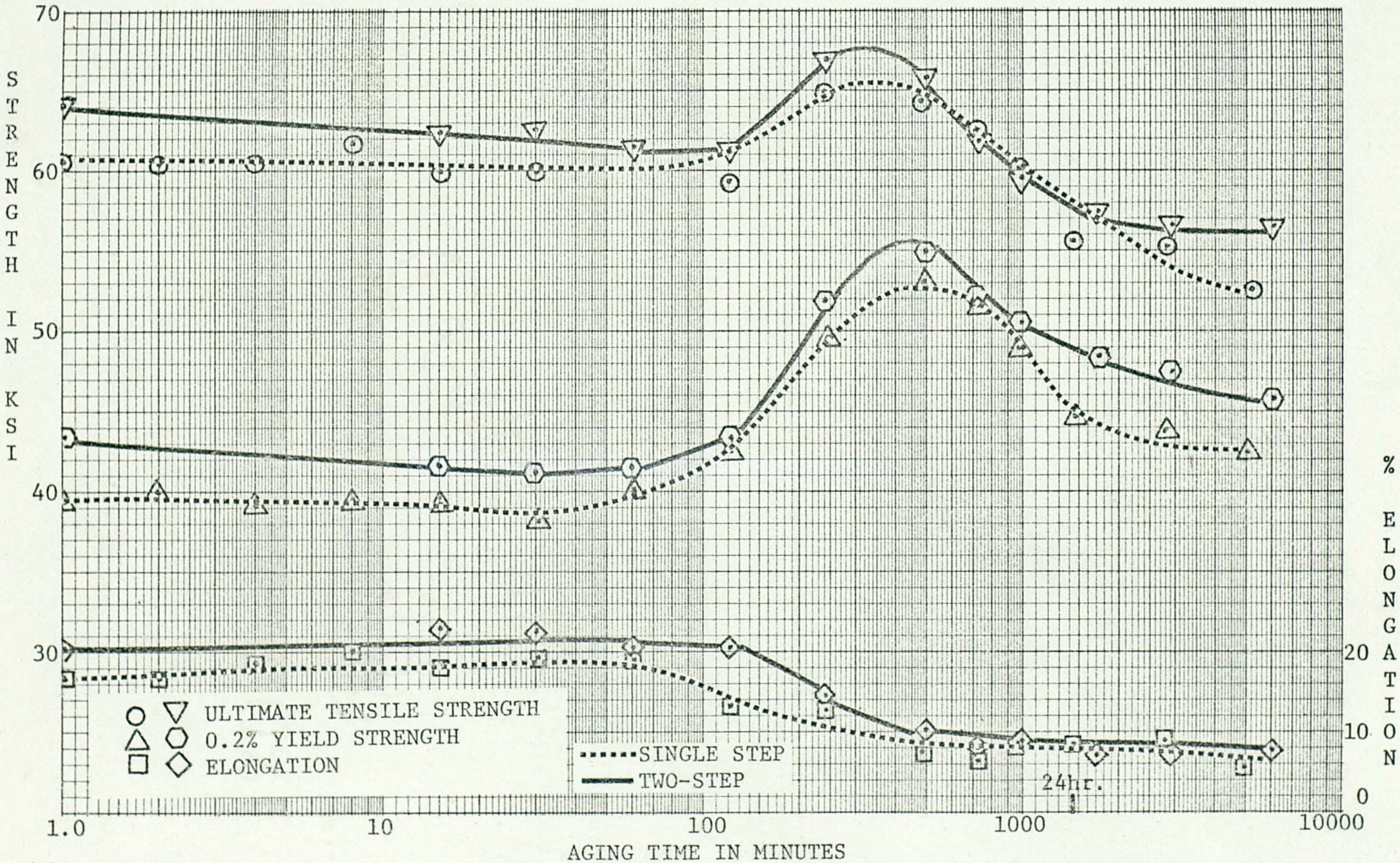


Fig. 11.--A comparison of single-step aging at 190°C and preaging at 140°C for three days plus aging at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

The yield strength again followed the same trend as the UTS with an initial slight decrease in strength occurring in the pre-aged alloy. This was followed by a rapid increase in yield strength to 55.2 ksi after 8 hours aging at 190°C. Subsequently a slow decrease to 45.9 ksi occurred after 96 hours aging. The ductility remained at 21±3% until after the 2 hour aging, then the ductility fell to 10±2% in direct correlation to the increase in strength.

A comparison of the tensile properties of the alloy single-step aged at 190°C and the two-step aged treatment of 3 days at 140°C plus 190°C is shown in Fig. 11. The UTS values for the two-step aging treatment were slightly higher throughout the entire aging process. The peak values in UTS occurred at the 4 hour period in both cases. The UTS values of the two-step aged alloy did not decrease as rapidly as those of the single-step aged alloy in the 24 to 96 hour period. The yield strength values followed the UTS trend in values. The ductility of both alloys did not deviate significantly from one another.

QUENCH RATE STUDY

The effects of slow quenching in oil at 20°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy are shown in Fig. 12. The samples were solutionized for 20 minutes at 500°C (as for all previous tests). Upon aging at 190°C, a slight decrease in strength was observed in that the UTS fell from its as quenched value of 65 ksi to 63 ksi after the first 2 hours aging. In the 2 to 48 hour period the UTS values increased steadily to a peak value of 70.5 ksi. The UTS peak was followed by a rapid decrease to 50.0 ksi after 96 hours aging.

The yield strength followed the same trend as the UTS. A slight decrease in strength was observed in the first hour of aging. This was followed again by a rapid increase to 58.2 ksi after 12 hours. Subsequently, a sharp decrease in yield strength occurred during the 12 to 96 hour period, resulting in a final value of 33.9 ksi.

The ductility as measured by the percent elongation did not change significantly with a constant value of 22±3% until after 60 minutes aging at 190°C. In the period between one hour and six hours aging at 190°C the elongation decreased rapidly from 22 to 10% while the UTS and yield strength correspondingly increased.

The tensile properties of the alloy water quenched and aged at 190°C as compared to those obtained by oil quenching and aging at 190°C are shown in Fig. 13. The UTS values for the oil quenched alloy are higher throughout the entire aging process, except

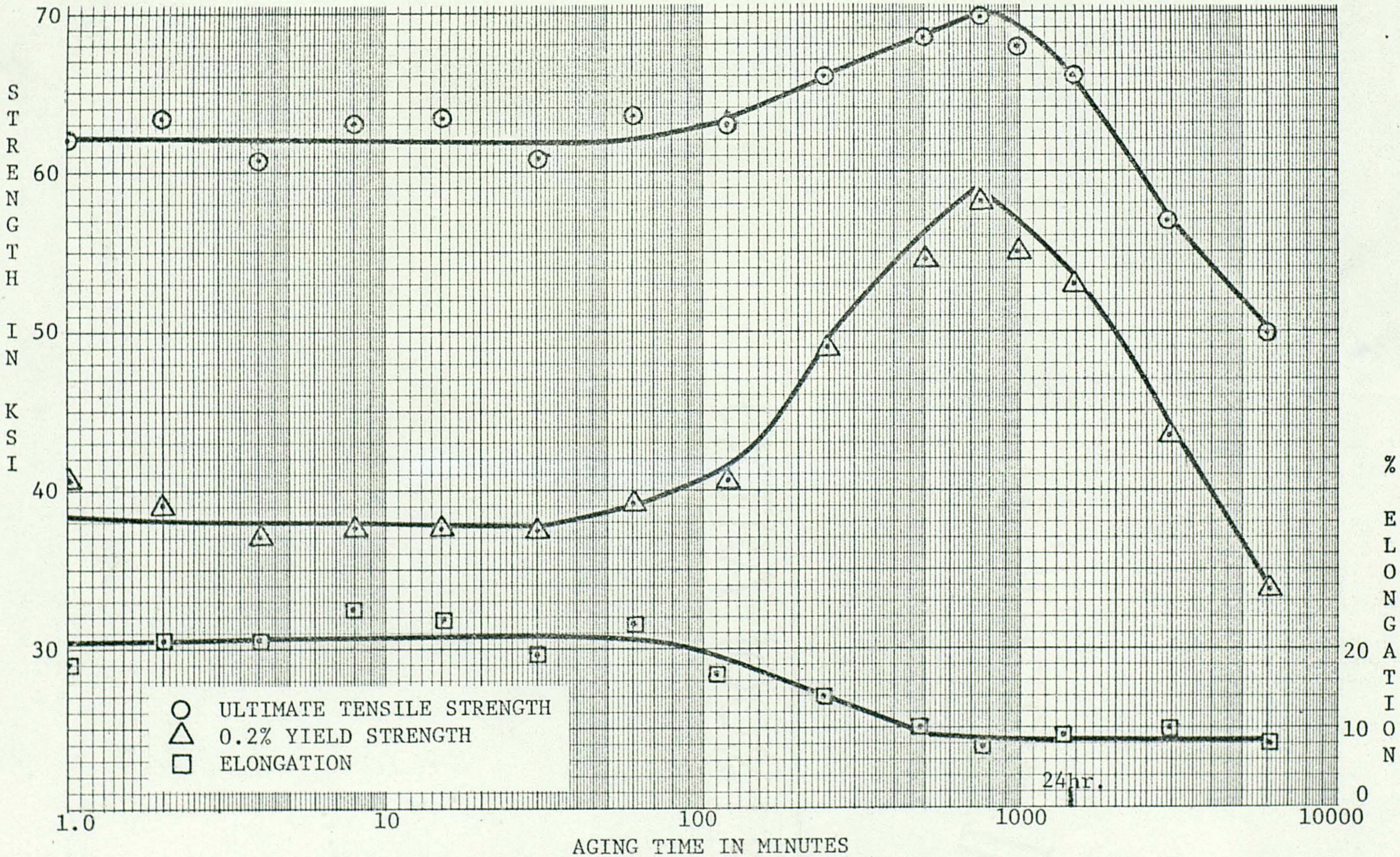


Fig. 12.--The effects of 20°C oil quench and single-step aging treatments at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

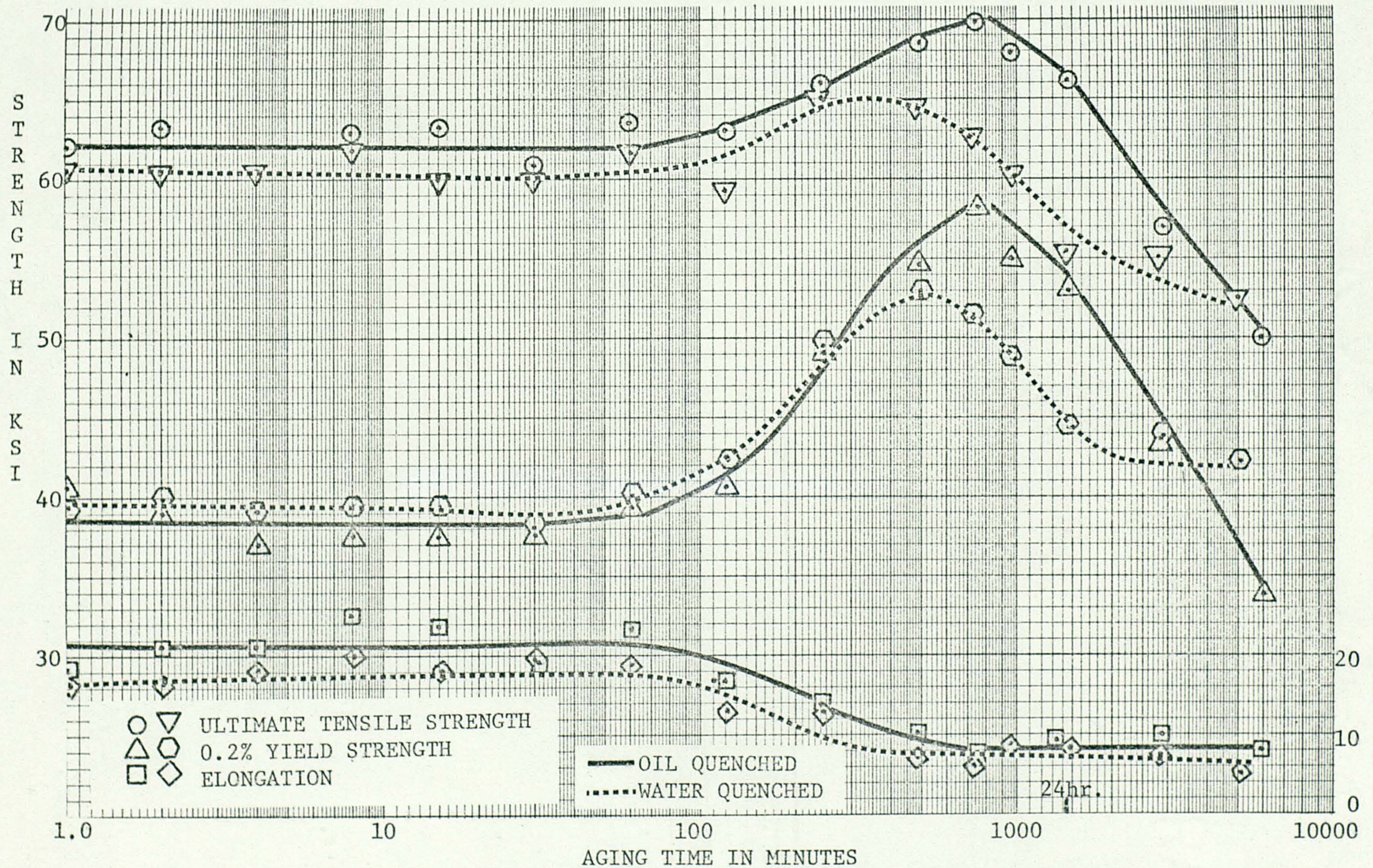


Fig. 13.--A comparison of oil quenched and water quenched (at 20°C) and aging at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

for the final aging (overaged), where they are about the same. The maximum UTS for the slow oil quenched alloy occurred after 12 hours aging while the maximum UTS of the fast water quenched alloy occurred between 4 and 8 hours.

The yield strength values showed the same trend with the maximum strength obtained by oil quenched and aged at 190°C for 12 hours being 5 ksi higher than the water quenched and aged alloy. The maximum yield strength of the oil quenched and aged material occurred 4 hours after the water quenched alloy. After 96 hours at 190°C (very overaged) the yield strength of the oil quenched alloy dropped gradually to 33.9 ksi. There appeared to be no significant difference in the ductility of the alloy water or oil quenched and aged at 190°C throughout the whole aging process.

DIRECT QUENCHING STUDY

The effects of quenching to the aging temperature of 190°C in oil on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy are shown in Fig. 14. The samples were solutionized for 20 minutes at 500°C. Upon aging a gradual increase in the UTS was observed from the early aged value of 60.0ksi to the peak at 24 hours aging with a value of 69.0 ksi. The UTS was followed by a rapid decrease to 60 ksi after 96 hours.

The yield strength followed the same trend as the UTS. A steady increase in yield strength occurred to the 4 hour period. The yield strength then increased rapidily to a value of 57.9 ksi in 24 hours. Subsequently, a sharp decrease in yield strength occurred during the 24 to 96 hour period, resulting in a final value of 48.7 ksi. The ductility as measured by the percent elongation did not change significantly with a constant value of 19 2%, until after the 30 minute aging at 190°C. In the period between 30 minutes and 2 hours the elongation decreased from 19 to 14%. A rapid decrease occurred in the period from 2 hours to 8 hours decreasing to 4%. The UTS and yield strength correspondingly increased.

The tensile properties of the alloy water quenched and aged at 190°C as compared to those obtained by direct oil quenching and aging at 190°C are shown in Fig. 15. The UTS values for the oil quenched and direct aged alloy are greater throughout the aging.

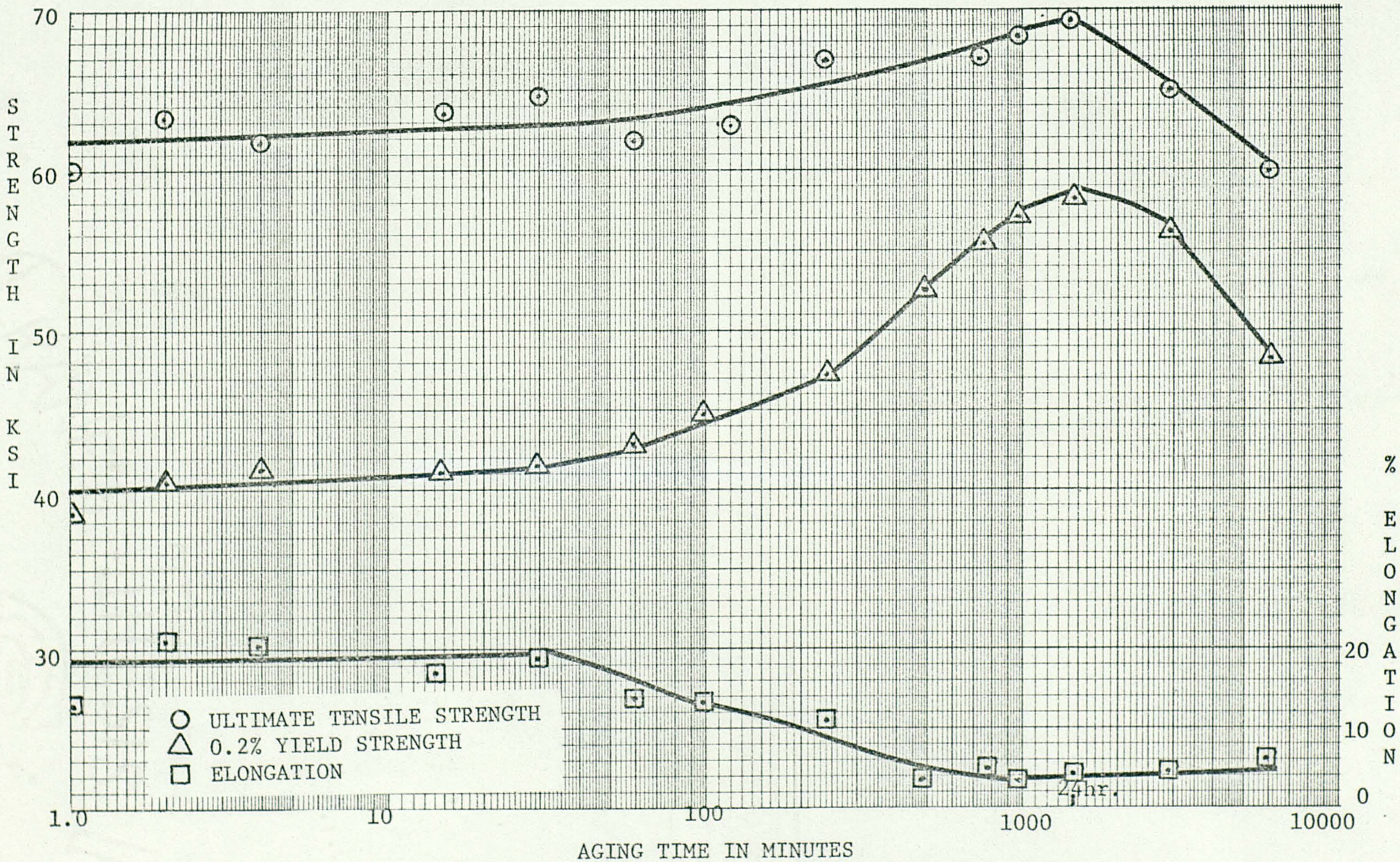


Fig. 14.--The effects of direct oil quench to 190°C and aging at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

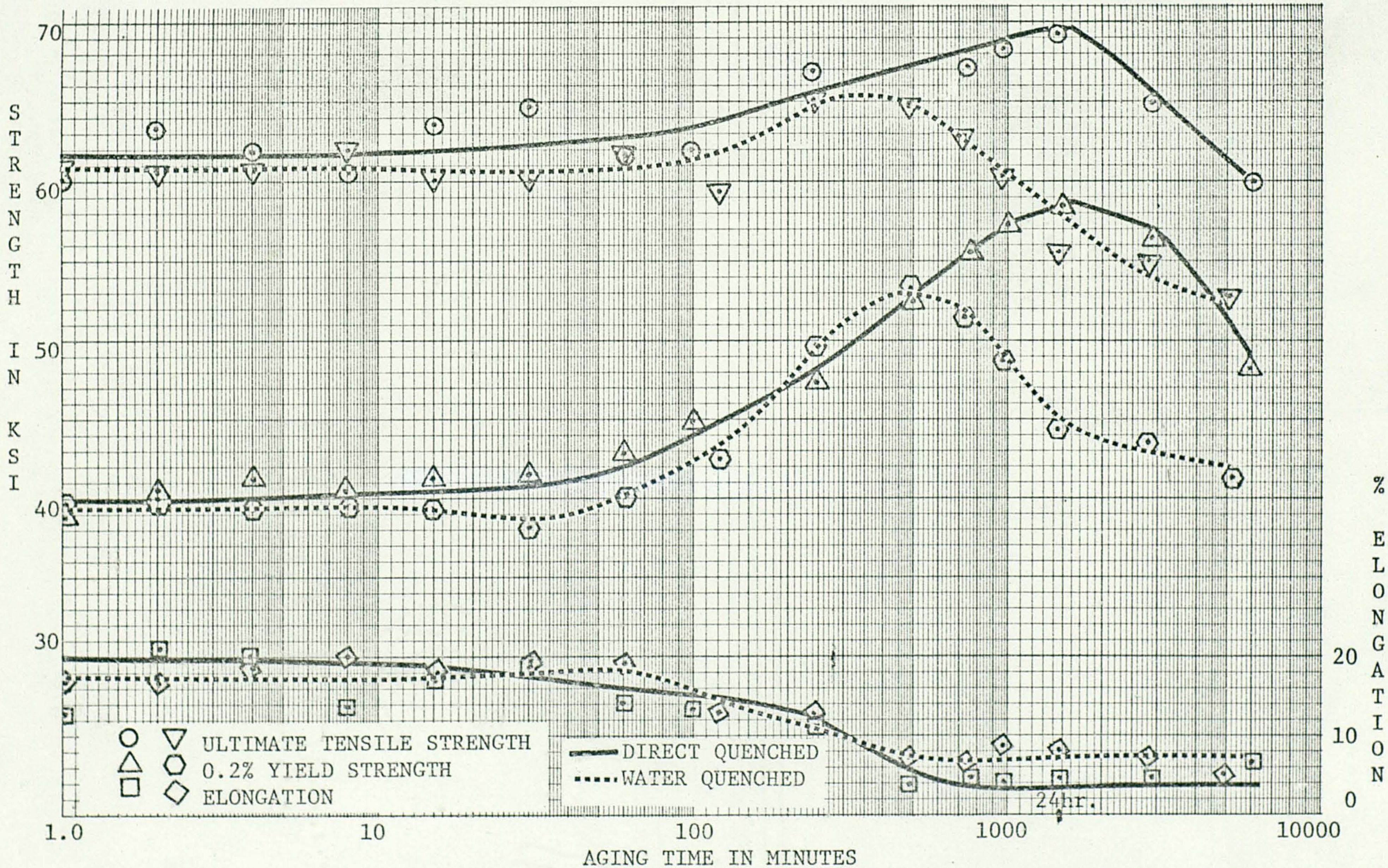


Fig. 15.-- A comparison of direct oil quench (to 190°C) and water quench (to 20°C) and aging at 190°C on the tensile properties of the Al-4.5%Cu-1.5%Mg alloy.

The peak of the water quenched data occurred in the 8 hour period. The direct quenched and aged alloy continued to increase in strength to 69.0 ksi after 24 hours aging while the water quenched and aged alloy (190°C) lost its strength falling to a value 5 ksi less then the direct aged alloy at the 24 hour period. There was no significant difference in the ductility of the two different aging treatments until after the 16 hour aging period. After the 16 hours the water quenched alloy showed slightly greater ductility.

REVERSION STUDY

After first aging the alloy for 10 hours at 190°C following a water quench, the UTS was 59.2 ksi and the yield strength was 50.5 ksi. After 15 minutes at 250°C the UTS dropped to 53.3 ksi. There was no significant decrease in the UTS when additional samples were reverted at 275°C for 15 minutes. At temperatures greater than 275°C there was gradual decrease to a value of 44.1 ksi at 350°C. The yield strength decreased in value following the same trend as the UTS. In the interval from 250 to 275°C a slight decrease occurred, this was followed by a consistant drop in yield strength to a value of 21.4 ksi at 350°C. The elongation indicated a gradual increase in value from 4.6 ksi in the aged condition to 10.3 ksi over the entire reversion temperature range. The changes to the UTS, yield strength and elongation are shown in figure 16.

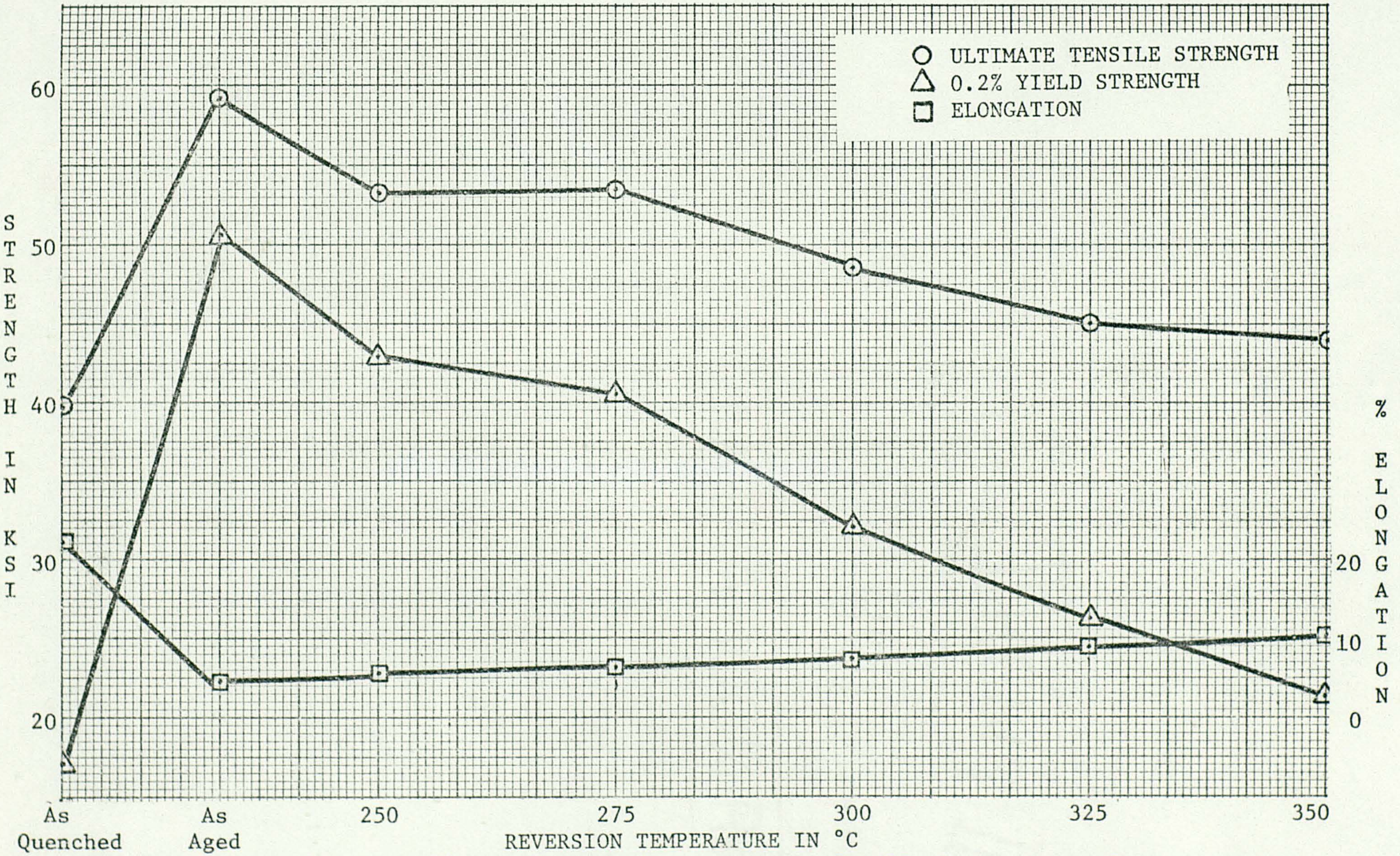


Fig. 16.--The effects of reversion treatments for 15 minutes at various temperatures on the tensile properties of a fully aged Al-4.5%Cu-1.5%Mg alloy.

## DISCUSSION

### Single-Step Aging

The results obtained for the single-step aging experiments can be compared to published data [3,6,20,22] of alloys of similar composition. The difference in copper and magnesium content has been known to significantly influence the time to achieve peak hardness [3]. The published hardness curves of Hardy [3] and Silcox [6] indicate increase to peak hardness at 110°C,130°C,165°C and 190°C of the aluminum-3.1%copper-1.5%magnesium alloy. This earlier data agrees with the results which were obtained through the tensile tests of this experimentation when consideration is given to the accelerating effect of additional copper [3].

Silcox [6] correlated hardness data with x-ray diffraction analysis and identified the precipitates that are formed at each stage along the hardness verses time curves for single-step aging. The GPB zones formed initially and were followed by the S' precipitate. Aging for longer times and higher temperatures indicated that S' and S precipitates did form. The formation of the S' precipitate is noted as an increase in the strength of the alloy with a corresponding reduction of the elongation. The S' precipitate is primarily nucleated heterogenously on dislocations [13]. The growth of this precipitate occurs due to accommodation of the dislocations with the strain due to the misfit of the precipitate with the matrix.

The aging data of 190°C indicates the formation of the S' precipitate. This precipitate impeades the glide of dislocations through the matrix and therefore increases the strength of the material. The S' precipitate is indicated by a maximum on the strength verses log time curve which reaches the peak in 6 to 8 hours for 190°C aging. The 0.2% yield strength changes concomittently with the peak in the UTS curve. The loss of elongation due to the formation of the S' precipitate can be seen in the graphical data presentation of figure 3. The drop from 20% to 7% associated with the increase is a result of the difficulty for dislocations to pass through the S' lath network.

The evaluation of the single-step aging curves at 140°C,160°C and 190°C indicates that two distinct stages of strengths are formed. In the initial stage a homogenous distribution of the GPB zones form and result in an increase in strength with no change in elongation. This precipitate forms upon quenching and grows rapidly in a few minutes. The S' precipitate which is a metastable form of S phase ($Al_2CuMg$) forms after prolonged aging at the higher temperatures. The single-step aging evaluations were performed to study the basic precipitation mechanisms in the Al-4.5%Cu-1.5%Mg alloy. The existence of the S' intermediate precipitates are accommitted with the peak and the simultanous loss of ductility.

Two-Step Aging

The two-step aging process is a multi-isothermal treatment following the solutionizing and quenching operation. The alloy is first aged (refered to as preaged) at a given temperature for a period of time, and then is aged at a second time at a higher temperature. The first aging step is intended to produce a finely dispersed precipitate which will contribure to mechanical strength and set-up nuclei for the second step of aging. The two-step treatment when properly used will result in a stabilized GPB precipitate that will contribute to the aging effects at a second aging temperature. Previous work by Smith [18], Polmear [13], Pashley [19] and Singh [14] has indicated that a higher strength alloy can result in some cases from two-step aging.

The two-step aging of Al-4.5%Cu-1.5%Mg resulted in a small increase in the strength of the alloy using 3 days at 140°C plus 190°C treatment. The two-step aging treatment with 80°C for 168 hours followed by aging at 160°C or 190°C resulted in a slight decrease in strength. In studying an Al-3.3%Cu-1.6%Mg alloy, Sen and West [11] found that 72 hours at 130°C plus 190°C resulted in improved hardness. They believed that the S' laths formed during preaging at 130°C nucleated the larger laths formed at the second higher aging temperature. This therefore resulted in a denser distribution of S' and the higher hardness. The hardness obtained by Singh and Malik [14] for two-step aging at 140°C plus 190°C also showed that the 140°C preaging was effective in producing higher hardness values. Since the GPB zones do not nucleate the S' phase, two-step aging first at a lower temperature for optimum GPB formation and then at a higher temperature will not result in increased S' formation. The contribution of the GPB zones are evident in the early stages of aging at lower temperatures. The contributions of the S' precipitate are significant at greater times and temperatures. Two-step aging to further enhance the S' formation and hence the peak strengths is accomplished with the 140°C plus 190°C treatments. The 80°C first stage aging is insufficient to provide stable nuclei at the 190°C temperature so as to improve the peak strengths of the alloy.

Quench Rate Study

The influence of quence rate upon the mechanical properties of aluminum-copper-magnesium alloys has been the topic of discussion in several technical studies [6,8,15,16]. In this present investigation it has been found that higher strengths are obtained by a slower quenching rate for the alloy studied. This increased strength is believed to be attributed to the creation of a fine dispersion of S' intermediate precipitates formed during the slow quench. Subsequent aging at 190°C will result in denser S' precipitates and hence higher strengths. This hypothesis will have to be verified by an electron microscope study of the precipitate distributions.

Silcox [6] also noted the increased hardness after using a slow acetone quench over values obtained by water quenching and aging. The aging treatments she used were single-step from 130°C to 190°C. The quench rate data of Silcox [6] was evaluated with the x-ray diffraction analysis and hardness measurements. According to Silcox [6] :

> "... a slower rate of quenching of the single crystals gives a higher peak hardness at 130-190°C than a faster quench rate."

As in the case of the two-step aging treatments of the previous section, the nuclei formed during the slow quench enhanced precipitation of the S' precitate at the aging temperature. This more optimum treatment by virture of the distribution and size of the S' precipitate results in increased strength.

Direct Quenching Study

The technique of direct quenching results in a quench from the solutionizing temperature to the aging temperature. The amount of undercooling is less with this treatment and results in a thermal treatment that places the material directly at the aging temperature. The influence of this type of treatment can be significant upon the nucleation rate of the precipitates. Comparison of the data of direct quenched and water quenched samples indicates the influence of direct quenching upon the aged alloy. The higher values of tensile strengths of the direct quenched material which occur later in time than the water quenched alloys indicate a more optimum dispersion of precipitates.

It is believed here again as in the slow quench study, a fine dispersion of S' intermediate precipitate is formed by direct quenching to 190°C and aging. This will result in higher strengths.

Reversion Study

The phenomena of reversion is a resolution of the precipitate by heating at a temperature which is above that of the original aging condition. The reversion temperature is below the equilibrium solvus. The direct observation of the phenomena in thin foils with the electron microscope by Hren and Thomas [23] has added to the understanding of the process.

Reversion data in connection with an evaluation of aluminum-copper-magnesium has been used by Benton and Rollason [10] and Sen and West [11]. The reversion data presented by Benton and Rollason [10] includes aluminum-3.4% copper-1.4% magnesium. The aluminum-4.5% copper-1.5% magnesium reversion data of this study agrees with the published hardness reversion data. The formation of precipitates upon aging at 190°C for 10 hours results in heterogenous S' laths with GPB zones. The resistivity work by Singh and Mallik [14] indicates a reversion of GPB at 260°C which agrees with the published results of Sen and West [11].

The gradual decrease in strenght properties following the 250°C to 325°C reversion treatments indicate resolution (reversion) of the GPB zones and the coarsening of S' intermediate precipitates. This process occurs slowly as is indicated by the slope of the reversion curve. The type two reversion process as presented by Smith [24] is known to occur at the temperature and composition which was evaluated. The difficulty expressed by Benton and

Rollason [10] was due in part to the formation of the S' precipitates which grew at the temperatures for GPB reversion. The technique used in this study produced a matrix of both precipitates. The reversion was therefore a matter of degree of reversion due to the multiple precipitate concentration of the matrix.

# CONCLUSIONS

1. Using single-step aging a maximum value of 67 ksi UTS was produced by aging at 160°C for 24 hours.

2. Two-step aging for 3 days at 140°C plus 190°C resulted in a slight increase in strength over the single-step aging treatments at 190°C.

3. Slow (oil) quenching followed by aging at 190°C produced higher strengths than water quenching and aging at 190°C.

4. Direct quenching to 190°C followed by aging at 190°C produced higher strengths (of about the same as a slow oil quench) than water quenching and single-step aging at 190°C.

5. Reversion of this alloy occurs slowly over the temperature range 250°C to 350°C indicating a gradual resolution of the GPB zones and coarsening of the S' precipitate.

# RECOMMENDATIONS FOR FURTHER STUDY

The identification of the specific phase with the transmission electron microscope and x-ray diffraction analysis is recommended to complete the evaluation. The influence of quenching conditions upon the mechanical and corrosion properties of the alloy should be developed. A recent review by Fine [21] has indicated the significance of this alloy system for fatigue and higher temperature applications.

APPENDIX

TABLE 3

SINGLE-STEP AGING AT 140 °C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quenched in water at 20°C, age at 140°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation percent |
|---|---|---|---|
| As Q | 39.8 | 17.3 | 22.3 |
| 2 min. | 63.5 | 41.9 | 23.0 |
| 4 min. | 63.3 | 42.0 | 22.5 |
| 6 min. | 63.6 | 41.6 | 23.0 |
| 15 min. | 62.6 | 41.7 | 22.5 |
| 30 min. | 62.2 | 40.8 | 20.0 |
| 60 min. | 63.5 | 41.5 | 20.5 |
| 2 hr. | 63.5 | 41.5 | 23.5 |
| 4 hr. | 62.9 | 41.3 | 23.5 |
| 8 hr. | 62.3 | 41.2 | 25.0 |
| 16 hr. | 63.5 | 41.5 | 23.0 |
| 24 hr. | 62.8 | 40.9 | 22.8 |
| 48 hr. | 62.0 | 41.0 | 21.3 |
| 72 hr. | 63.8 | 43.0 | 21.8 |
| 168 hr. | 64.3 | 45.3 | 21.0 |

TABLE 4

SINGLE-STEP AGING AT 160 °C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quenched in water at 20°C, age at 160°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation percent |
|---|---|---|---|
| As Q | 39.8 | 17.3 | 22.3 |
| 2 min. | 64.0 | 41.6 | 25.0 |
| 4 min. | 64.5 | 40.3 | 17.5 |
| 8 min. | 64.3 | 40.2 | 18.7 |
| 15 min. | 63.6 | 39.8 | 23.7 |
| 30 min. | 63.3 | 39.5 | 25.0 |
| 60 min. | 64.0 | 40.0 | 25.0 |
| 2 hr. | 63.7 | 39.5 | 23.7 |
| 4 hr. | 64.3 | 41.1 | 23.1 |
| 8 hr. | 65.1 | 41.4 | 25.0 |
| 10 hr. | 64.7 | 41.3 | 23.4 |
| 12 hr. | 65.0 | 41.7 | 23.8 |
| 16 hr. | 64.6 | 41.8 | 23.7 |
| 24 hr. | 65.3 | 44.0 | 24.3 |
| 53 hr. | 65.2 | 51.2 | 18.1 |
| 72 hr. | 67.5 | 52.6 | 14.9 |
| 96 hr. | 66.3 | 52.9 | 12.0 |
| 144 hr. | 63.4 | 51.4 | 9.0 |

TABLE 5

SINGLE-STEP AGING AT 190 °C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quenched in water at 20°C, age at 190°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation percent |
|---|---|---|---|
| As Q | 39.8 | 17.3 | 22.3 |
| 1 min. | 60.8 | 38.8 | 17.3 |
| 2 min. | 60.4 | 40.0 | 16.5 |
| 4 min. | 60.8 | 39.2 | 19.1 |
| 8 min. | 61.9 | 39.6 | 20.0 |
| 15 min. | 60.5 | 39.3 | 18.1 |
| 30 min. | 60.0 | 38.4 | 19.5 |
| 60 min. | 61.8 | 40.0 | 19.0 |
| 2 hr. | 59.2 | 42.5 | 13.3 |
| 4 hr. | 65.2 | 49.4 | 12.9 |
| 8 hr. | 64.6 | 53.2 | 7.8 |
| 12 hr. | 62.3 | 51.7 | 6.8 |
| 16 hr. | 60.2 | 49.0 | 9.0 |
| 24 hr. | 55.9 | 45.0 | 8.5 |
| 48 hr. | 55.0 | 43.8 | 8.5 |
| 96 hr. | 52.7 | 41.3 | 5.0 |

TABLE 6

TWO-STEP AGING AT 80°C FOR
ONE WEEK PLUS 160°C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes , quench at 20°C in water, 80°C for one week then age at 160°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation percent |
|---|---|---|---|
| As Preaged | 64.1 | 42.5 | 19.5 |
| 1 hr. | 60.6 | 39.1 | 22.5 |
| 4 hr. | 60.0 | 39.6 | 22.0 |
| 6 hr. | 61.7 | 40.3 | 24.0 |
| 8 hr. | 61.9 | 41.3 | 23.3 |
| 10 hr. | 63.0 | 43.0 | 24.0 |
| 14 hr. | 64.5 | 42.8 | 24.0 |
| 16 hr. | 61.3 | 41.6 | 22.1 |
| 24 hr. | 61.5 | 43.0 | 20.7 |
| 48 hr. | 64.8 | 51.5 | 15.3 |
| 96 hr. | 64.5 | 55.5 | 10.5 |

TABLE 7

TWO-STEP AGING AT 80°C FOR
ONE WEEK PLUS 190°C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quench at 20°C in water, 80°C for one week, then age at 190°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation percent |
|---|---|---|---|
| As Preaged | 64.2 | 43.4 | 24.8 |
| 1 hr. | 58.9 | 38.7 | 16.2 |
| 2 hr. | 58.1 | 40.9 | 16.8 |
| 4 hr. | 60.8 | 49.5 | 10.6 |
| 6 hr. | 61.8 | 53.4 | 8.6 |
| 8 hr. | 59.9 | 51.1 | 9.4 |
| 10 hr. | 58.7 | 50.8 | 9.8 |
| 12 hr. | 58.8 | 50.8 | 9.4 |
| 16 hr. | 56.9 | 48.7 | 10.0 |
| 24 hr. | 58.1 | 48.4 | 10.0 |
| 48 hr. | 56.3 | 45.7 | 9.0 |
| 96 hr. | 55.8 | 44.5 | 9.6 |

TABLE 8

TWO-STEP AGING AT 140°C FOR
72 HOURS PLUS 190°C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quench at 20°C in water, 140°C for 72 hours, then age at 190°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation percent |
|---|---|---|---|
| As Preaged | 64.1 | 43.6 | 21.0 |
| 15 min. | 62.4 | 41.8 | 23.5 |
| 30 min. | 62.6 | 41.2 | 23.0 |
| 60 min. | 61.6 | 41.7 | 20.5 |
| 2 hr. | 62.6 | 43.6 | 21.0 |
| 4 hr. | 67.0 | 52.0 | 14.5 |
| 8 hr. | 65.9 | 55.2 | 10.5 |
| 12 hr. | 61.9 | 52.2 | 8.0 |
| 16 hr. | 59.5 | 50.7 | 8.8 |
| 28 hr. | 57.7 | 48.6 | 7.8 |
| 48 hr. | 56.5 | 47.2 | 8.0 |
| 96 hr. | 56.5 | 45.9 | 8.0 |

TABLE 9

SINGLE-STEP AGING AT 190°C
OIL QUENCHED AT 20°C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quenched in oil at 20°C, age at 190°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation Percent |
|---|---|---|---|
| As Q | 65.0 | 40.9 | 22.3 |
| 1 min. | 63.6 | 39.6 | 18.5 |
| 2 min. | 63.5 | 39.1 | 21.3 |
| 4 min. | 61.8 | 37.5 | 21.3 |
| 8 min. | 63.2 | 37.8 | 25.0 |
| 15 min. | 63.4 | 37.8 | 23.8 |
| 1 hr. | 63.9 | 38.9 | 24.0 |
| 2 hr. | 63.6 | 41.4 | 18.3 |
| 4 hr. | 66.0 | 48.8 | 14.0 |
| 8 hr. | 68.3 | 54.7 | 9.9 |
| 12 hr. | 70.5 | 58.2 | 8.4 |
| 16 hr. | 68.1 | 55.0 | 7.4 |
| 24 hr. | 66.2 | 53.1 | 9.0 |
| 48 hr. | 57.4 | 43.6 | 10.0 |
| 96 hr. | 50.0 | 33.6 | 8.0 |

TABLE 10

SINGLE-STEP AGING AT 190°C
DIRECT OIL QUENCH TO 190°C

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quenched in oil at 190°C, age at 190°C

| Aging Time | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation Percent |
|---|---|---|---|
| 1 min. | 60.0 | 39.0 | 16.3 |
| 2 min | 63.6 | 41.5 | 21.3 |
| 4 min. | 61.8 | 41.4 | 20.1 |
| 15 min. | 63.4 | 41.2 | 16.6 |
| 30 min. | 64.9 | 41.8 | 19.0 |
| 60 min. | 62.1 | 43.1 | 14.0 |
| 2 hr. | 62.7 | 45.0 | 14.0 |
| 4 hr. | 67.0 | 47.8 | 11.4 |
| 8 hr. | 63.3 | 52.8 | 3.8 |
| 12 hr. | 67.9 | 55.2 | 6.0 |
| 16 hr. | 68.5 | 56.9 | 4.3 |
| 24 hr. | 69.0 | 57.9 | 4.6 |
| 48 hr. | 65.0 | 56.2 | 5.3 |
| 96 hr. | 60.0 | 48.7 | 6.4 |

TABLE 11

REVERSION TREATMENTS

HEAT TREATMENT: Solid solution heat treatment at 500°C for 20 minutes, quench in water at 20°C, age at 190°C for 10 hours, quench at 20°C in water, then 15 minutes at 250°C, 275°C, 300°C, 325°C or 350°C

| Temperature | Ultimate Tensile Strength KSI | Yield Strength KSI | Elongation Percent |
|---|---|---|---|
| As Q | 39.8 | 17.3 | 22.3 |
| As Aged | 59.2 | 50.5 | 4.6 |
| 250°C | 53.3 | 42.9 | 5.8 |
| 275°C | 53.6 | 40.5 | 6.3 |
| 300°C | 48.6 | 32.1 | 7.3 |
| 325°C | 45.1 | 26.3 | 9.0 |
| 350°C | 44.1 | 21.4 | 10.3 |

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